Project ID: PM048_grant_2014

Pacific Northwest NATIONAL LABORATORY

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Tailored Materials for Improved Internal Combustion Engine Efficiency

(Agreement ID 23725)

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GENERAL MOTORS RESEARCH AND DEVELOPMENT

2014 DOE HYDROGEN PROGRAM AND VEHICLE TECHNOLOGIES PROGRAM ANNUAL MERIT REVIEW AND PEER EVALUATION MEETING

JUNE 19, 2014

WASHINGTON, DC

Overview

Timeline

- Start: late FY2011
- Project end date: Sept 2014
- Percent complete: 60%

Budget

- Total project funding
  - DOE - $1025k
  - GM - $900k (in-kind)
  - 50/50 Cost Share with GM through in-kind contribution
- DOE Funding for FY11: $200k
- DOE Funding for FY12: $350k
- DOE Funding for FY13: $300k
- DOE Funding for FY14: $125k

Barriers

Identified from 2011-15 MYPP Propulsion Materials Program

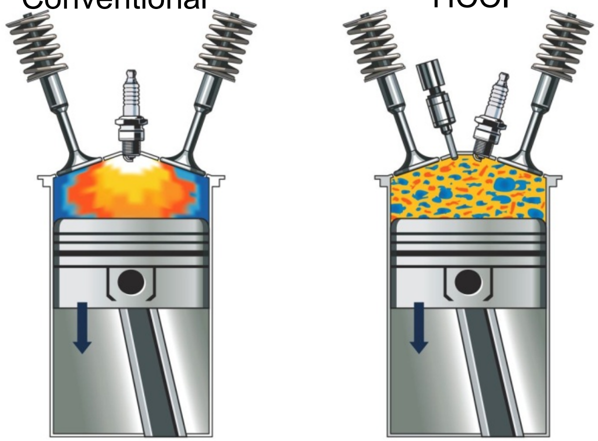
- New combustion strategies necessary for increased fuel efficiency are putting higher demands on traditional engine materials
  - Without better materials, gains can't be realized
- Lighter Weight Propulsion Materials
  - Weight of the propulsion system must be reduced even as the combustion régimes place higher strength requirements on the engine components
- Powertrain Cost
  - Light-duty vehicles are sensitive to upfront costs and heavy-duty vehicles are sensitive to lifecycle costs. Therefore any new materials technology will have to meet stringent cost targets to achieve commercial success.

Partners

- General Motors R&D
- University of North Texas
- Project lead: PNNL

Relevance – Problem Statement

New combustion strategies (HCCI, Low Temperature Combustion, lean burn, "High Speed" diesel) can increase engine efficiency

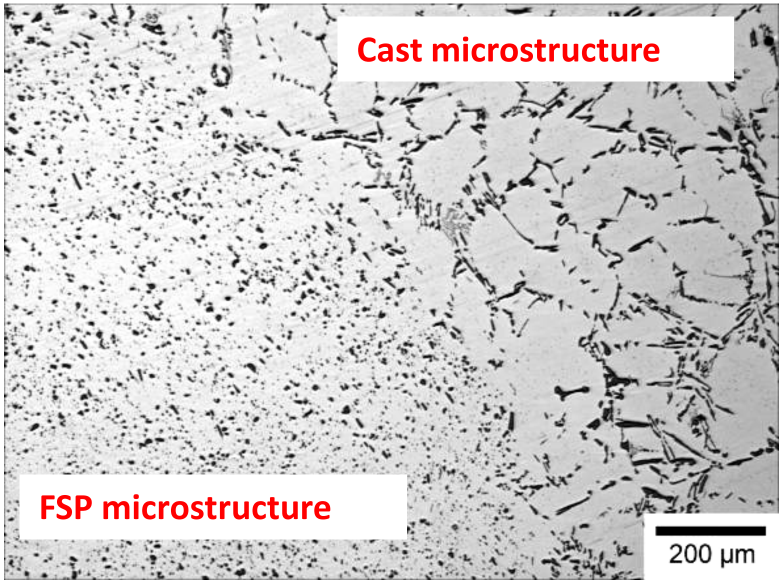


However,

- Peak cylinder pressures can be much higher than conventional engines leading to sharp load-rise times and high fatigue or thermal-fatigue loads on pistons, heads, cranks, blocks, etc.
- This can potentially require a change to higher cost materials (Ni alloys, Ti, CGI, Nodular Fe, forged micro-alloyed steels)

To enable the development of high-efficiency engines, a lower cost alternative may be to modify or tailor only the surface of the lower cost, conventional material to achieve the higher properties required.

Relevance
Friction Stir Processing Advantages



Process Advantages

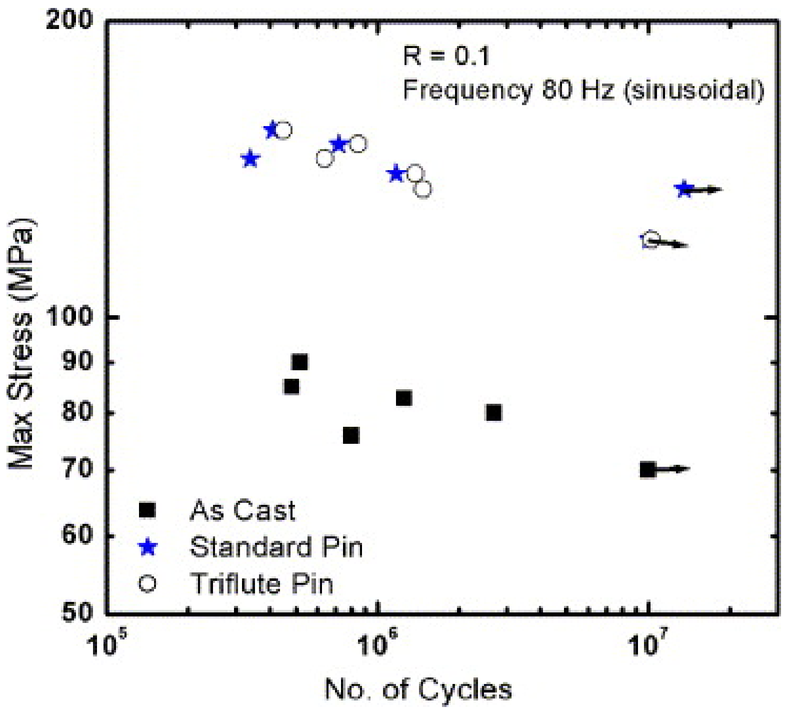
- FSP creates refined microstructure
  - Turns cast to wrought
  - Refines second phase particle and distributes it uniformly
- FSP can close porosity in castings
  - FSP eliminates surface and subsurface voids
- FSP can be used to form surface composites
  - Can "stir" insoluble ceramic or other components into surface in a solid state

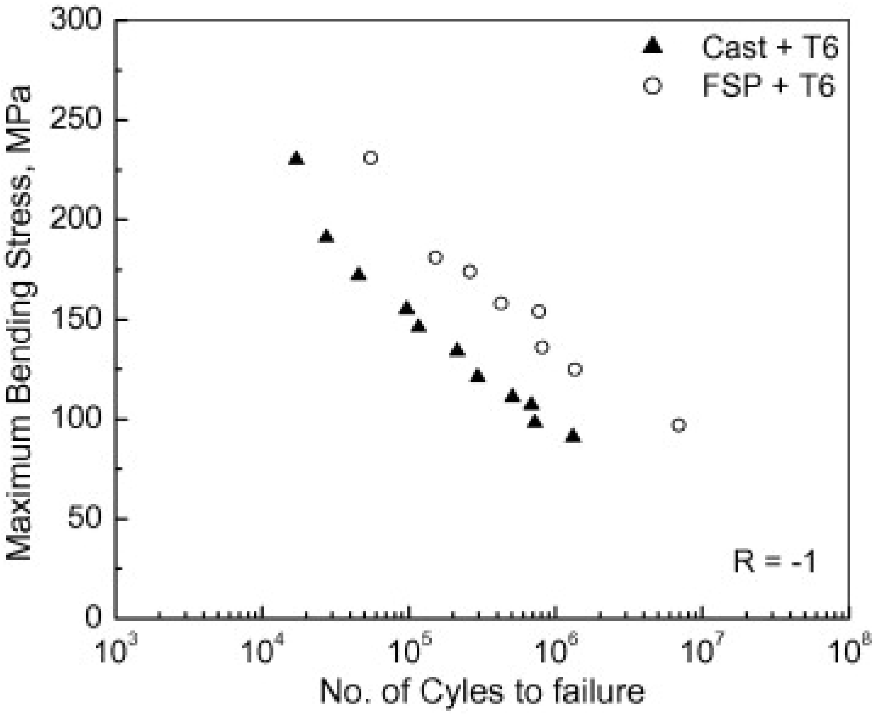
FSP can <u>selectively</u> modify an area of a part to produce better properties

- Strength improvement by 50%
- Ductility improvement by factor of 5
- FSP-processed materials have shown up to 80% improvement in endurance limit (fatigue strength) over as-cast alloys.
- FSP-processed materials have even shown from 5 to 15 times fatigue life improvement over investment cast material.

Relevance

Previous results show improved fatigue performance at room temperature for a cast microstructure





Enhancement of fatigue performance in a *sand cast A356 alloy* with a porosity vol. fraction ~ 0.95%. **Endurance limit improves by 80% as a result of FSP [1].**

5x enhancement in fatigue life after FSP in an *investment cast F357 alloy* [2]. This alloy had a porosity vol. fraction of only ~ 0.20%

FSP has been shown to dramatically improve fatigue performance, but will these improvements be realized at the high operating temperatures experienced by parts such as pistons and heads?

Relevance
Elevated Temperature Issues

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- Most strengthening mechanism that affect fatigue crack growth rate, including solid solution strengthening and grain size (dislocation-grain boundary interactions) are not as important at high temperature. However, other mechanisms like dispersion strengthening or 2nd phase particle interaction may still be active.

- Strain concentration from defects (porosity) or other notch geometries are still important for fatigue crack initiation regardless of temperature.

- At very high temperature conditions, other mechanisms like creep-fatigue may produce durability concerns that are not seen at low temperature.

- FSP gives us a knob to turn to adjust the microstructure to the best performance, it closes porosity and defects, it homogenizes 2nd phase particles and dendrites, and it can produce dispersions, it can produce coarse grain size through secondary recrystallization, all beneficial for elevated temperature fatigue resistance.

This project is developing the methods to use FSP to produce these various microstructures. We have found we can produce fine grained or coarse grained surfaces that have different and customized properties.
The question we are trying to answer is how do these different microstructures respond in fatigue at high temperature?

Relevance – Objective

Develop the Fundamental Science and Process of Friction Stir Processing

…to selectively produce surface modified regions on parts made from conventional, low-cost engine materials to address barriers related to durability at high Peak Cylinder Pressure (PCP)

Fabricate prototype friction stir processed components

…that can be tested for durability and performance so that designers of the combustion process can access areas of engine control where increased specific power and low emission levels are found, but where high PCPs can create reliability problems.

Project Focus Areas

Fatigue and Thermal fatigue improvement for aluminum cylinder heads

Rotating shaft fatigue improvement at fillet and oil hole locations on cast steel crankshafts to provide an alternative to higher cost forged steels

Approach

- Develop the FSP process parameters, tools, and techniques to produce defect-free FSP regions in plate materials with close microstructural analog to aluminum cylinder head alloys and cast steel crankshaft alloys.
- Complete coupon-level fatigue and creep fatigue testing of coupons
- If performance metrics are met, demonstrate this process on 2-D and 3-D geometry part analogs.
- Fabricate prototype parts to specifications provided by project partners and complete part testing (in-engine or other tests specified by partners).

Approach and Strategy for Deployment
TASK 1 Aluminum Alloy

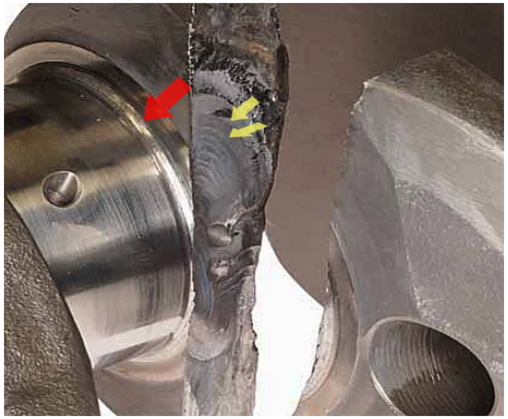
Cylinder Head Thermal-Fatigue, and Cylinder Head or Block "Room Temperature" Fatigue Life Improvement

- Produce chill-cast, Sr-modified A356 plate with SDAS approximately the same as a common cylinder head valve bridge area (GM R&D)(completed)
- Experimental FSP trials
  - By varying process parameters, develop coupons that display different microstructures (different grain size, peak temp, cooling rate, etc.(completed)
- Investigate heat treatment response
  - Iterate with the task above to produce coupon populations that either do or do not show secondary recrystallization (Abnormal Grain Growth –AGG) upon heat treatment(completed)
- Room temperature fatigue studies on FSP coupons (completed)
- Elevated temperature fatigue testing FSP coupons (in-progress)
- Creep Fatigue testing (cyclic "hold"-style test)
- Translate the process to 3-d part and produce a processed region on an actual head or head analog
- Operating temperature, cylinder head pressurization testing at GM
  - GM uses "steam tests" and "hydraulic fatigue tests" before parts move to dyno testing. A "steam test" is accomplished by clamping the cylinder onto a fixture and blowing steam of it, then running cold coolant through it to induce a thermal shock.

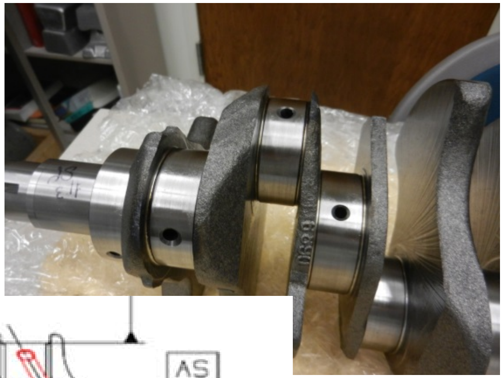
Approach and Strategy for Deployment
TASK 2 Cast Micro-alloyed Steel

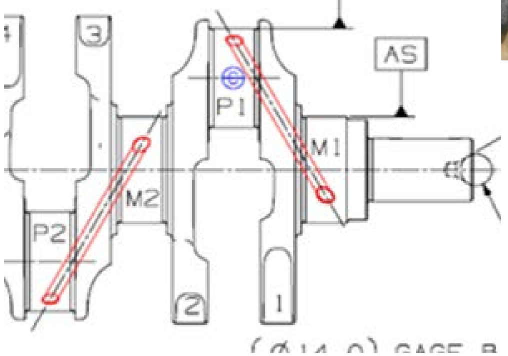
<u>Fillet, oil hole, and flange fatigue performance improvement on rotating shafts</u>

- FSP trials on cast, micro-alloyed steel plate for process parameter development
- Strength and toughness testing of FSP coupons
- Room temperature fatigue studies on FSP coupons (rotating beam fatigue on subscale specimens)
- Elevated Temperature fatigue (RBF) testing FSP coupons (oil bath temperature – this is not creep/fatigue, just fatigue)
- Translate process to 3-d part and producing a processed region on an actual rotating shaft assembly
- In-engine testing at GM? Or test house.



Fatigue failure at a fillet

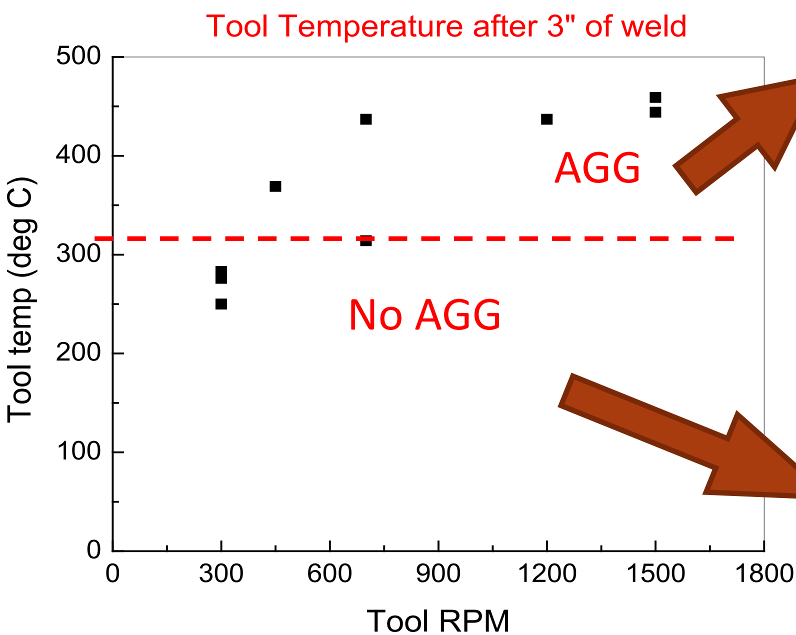


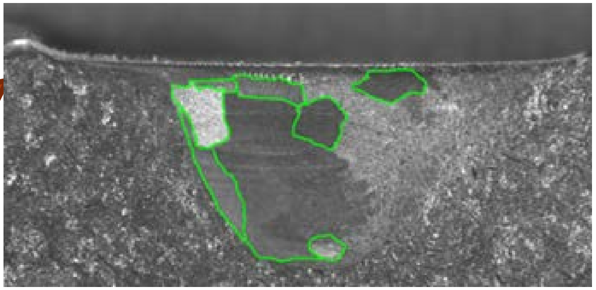


Oil hole chamfer fatigue

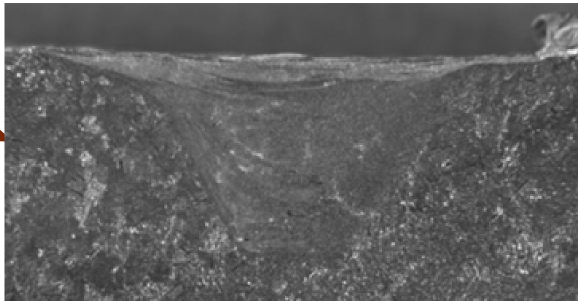
Technical Accomplishments and Progress

Reported last year: FSP – The role of process parameters





Microstructure of a 1500 RPM/ 4 IPM weld after post-weld heat treatment (PWHT). Large mm-sized grains (AGG).



PWHT = heating to 535ºC for 2.5 hrs followed by water quenching

Microstructure of a 300 RPM/ 6 IPM weld after post-weld heat treatment. Most of the weld nugget is comprised of fine grains.

- Plot shows the measured temperature in the tool as a function of tool RPM (thermocouple embedded in tool behind the FSW tool shoulder)
- Higher tool RPM at a fixed tool travel speed resulted in higher process temperature, which is expected.
- The processed microstructure, when subjected to an elevated temperature heat treatment, showed ***significant difference in grain coarsening behavior***

Welds with process temperature above 300ºC showed Abnormal Grain Growth (AGG), while welds with process temperature below 300ºC did not.

Technical Accomplishments and Progress
Task 1 Aluminum Head Alloy

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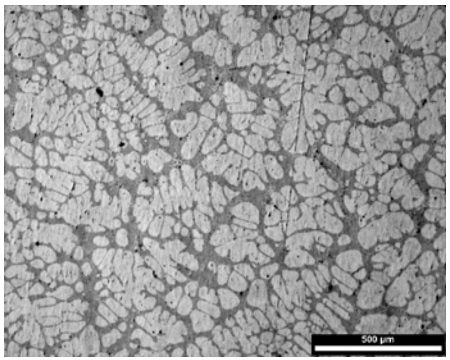
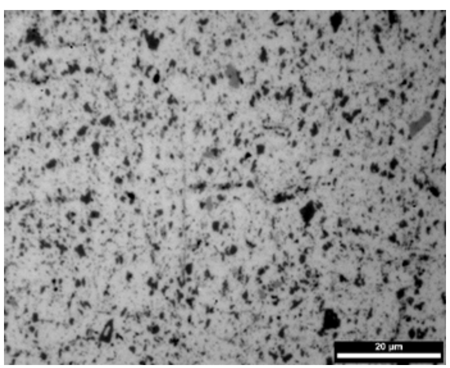
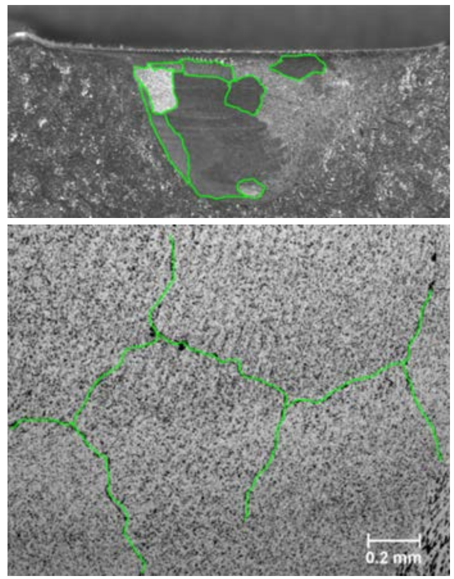
- We have produced, by using a wide range of processing conditions several different FSP microstructure that respond differently to aging and heat treating.
- We expect these microstructures to have different responses to fatigue and creep fatigue loading.



- As cast

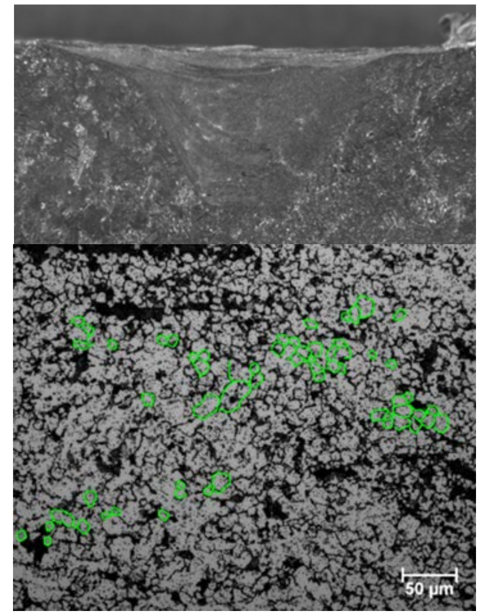


- As FSP



- Abnormal Grain Growth

After heat treatment



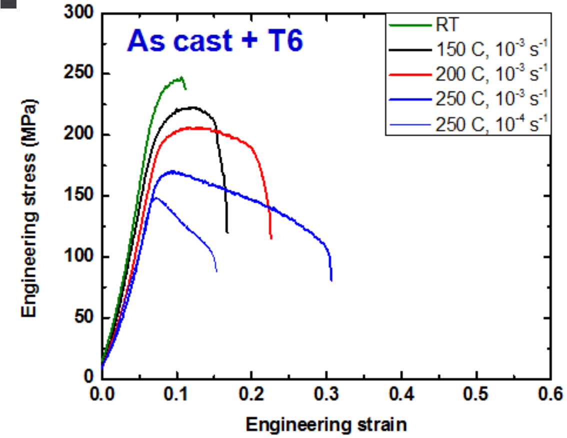
- No AGG

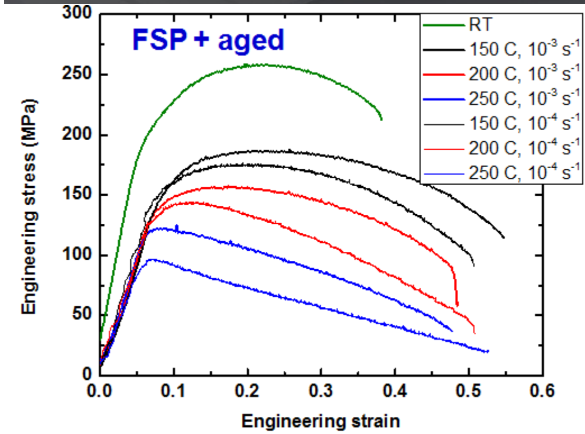
After heat treatment

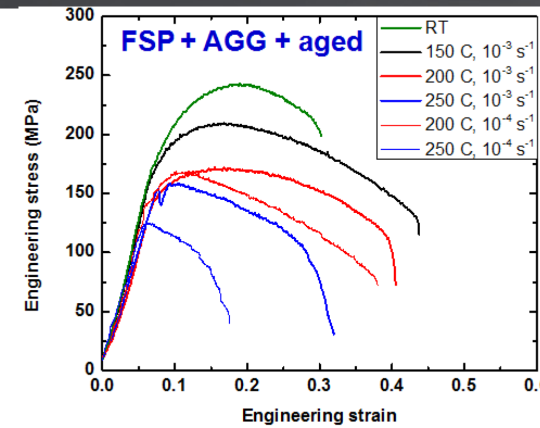
Using different FSW Process parameters we can either create or suppress AGG during heat treatment

Technical Accomplishments and Progress

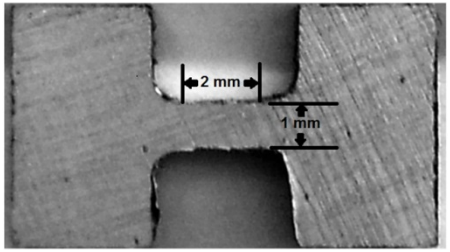
Summary of quasi-static miniature tensile testing







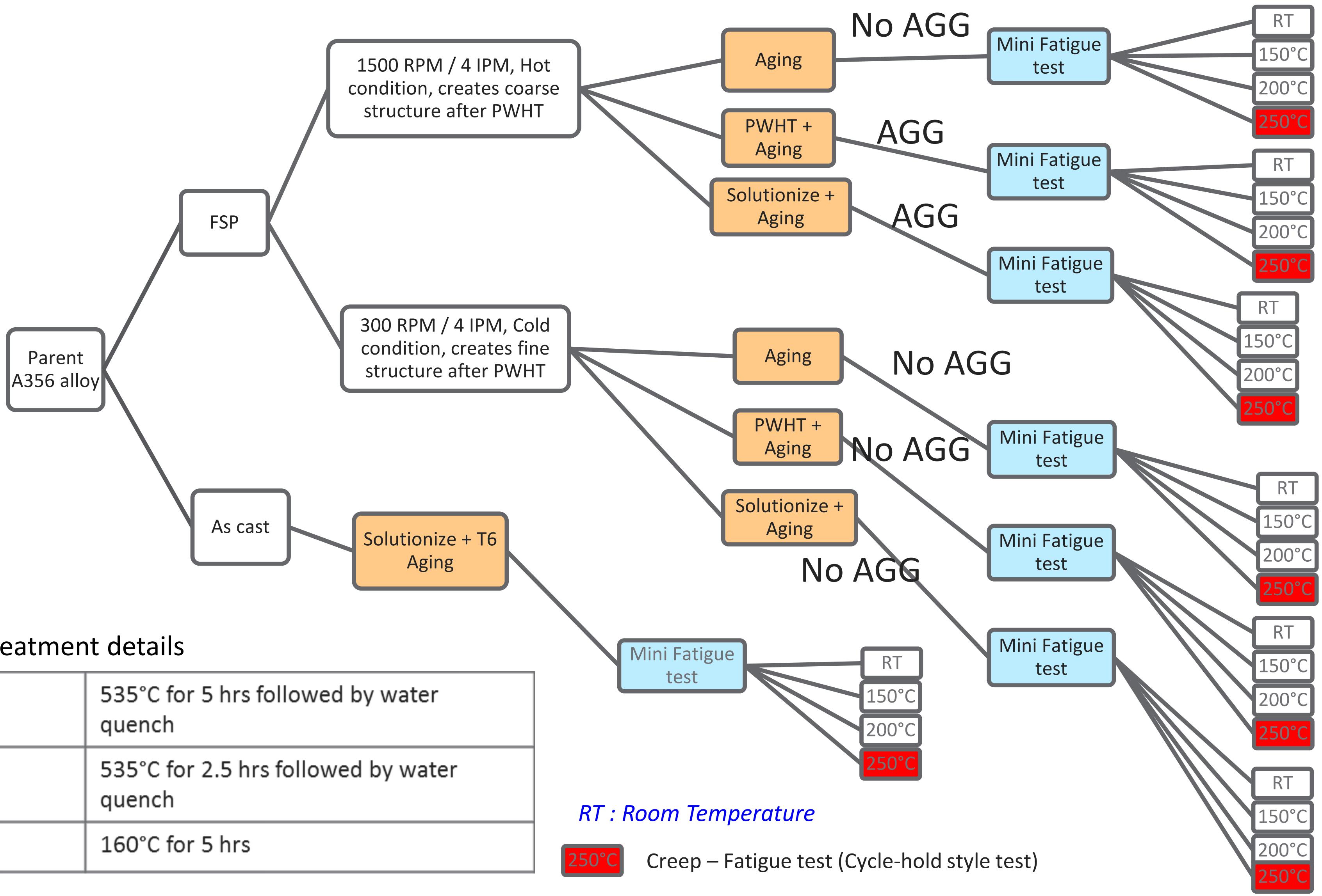
Condition	YS, Mpa				UTS, MPa				% El (Uniform)			
Strain rate: 1E-3	RT	150° C	200° C	250° C	RT	150° C	200° C	250° C	RT	150 ° C	200 ° C	250 ° C
As cast + T6	213	191	187	161	246	223	206	170	2.5	4	4	2
FSP	97	107	97	104	225	188	156	111	20	19	16	2.5
FSP + aged	177	137	126	114	259	187	158	123	21	12	10	2
FSP + AGG + Aged	166	165	139	153	243	210	172	159	22	9	9	2.5



Mini tensile test specimen

- % uniform elongation improves dramatically as a result of FSP. This is true of FSP unaged, aged (on a fine grained condition), and AGG aged (aged from a coarse grained condition).
- High ductility observed in FSP samples is related to the elimination of the dendritic structure, homogeneous distribution of Si particles, and the closure of casting porosity
- The coarse grained microstructure recovered most of the strength at elevated temperature yet gained a large amount of ductility at 150-200 C - (good for Fatigue)

Technical Accomplishments and Progress
Fatigue Testing Plan



Heat treatment details

Solution treatment	535°C for 5 hrs followed by water quench
PWHT	535°C for 2.5 hrs followed by water quench
Aging (T6)	160°C for 5 hrs

Technical Accomplishments and Progress
Fatigue testing details

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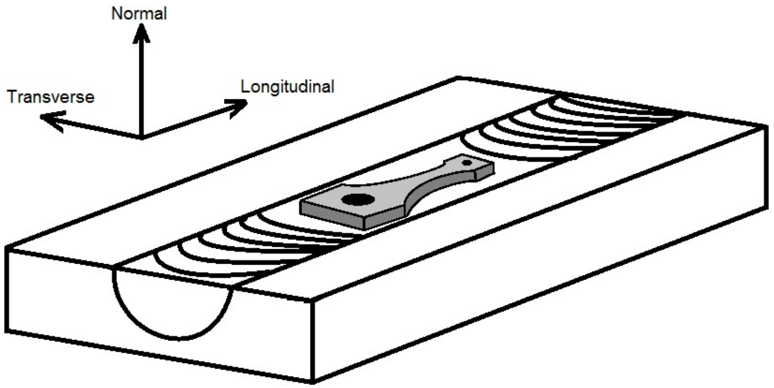
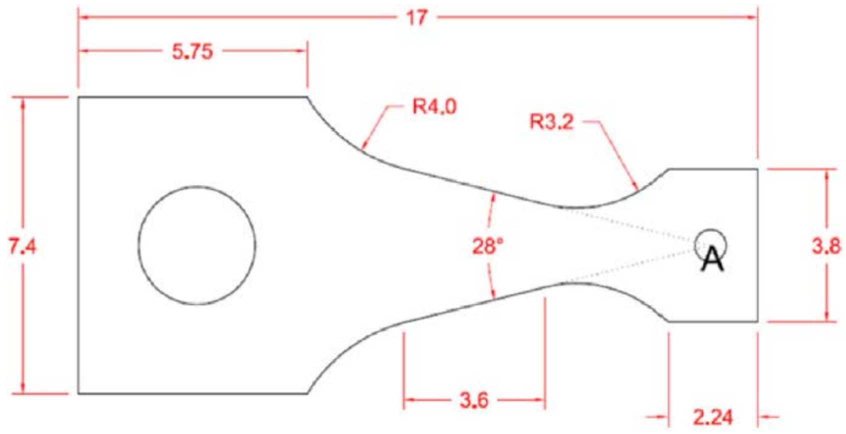
- Fatigue properties determined by conducting bending fatigue tests. Miniature sized specimens were used. The specimen details are shown in the figures below.



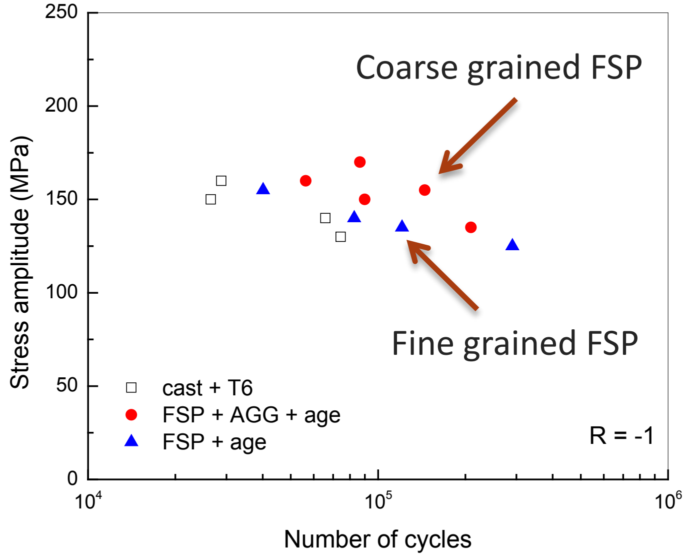
Orientation of the mini-fatigue sample with respect to the FSP run direction



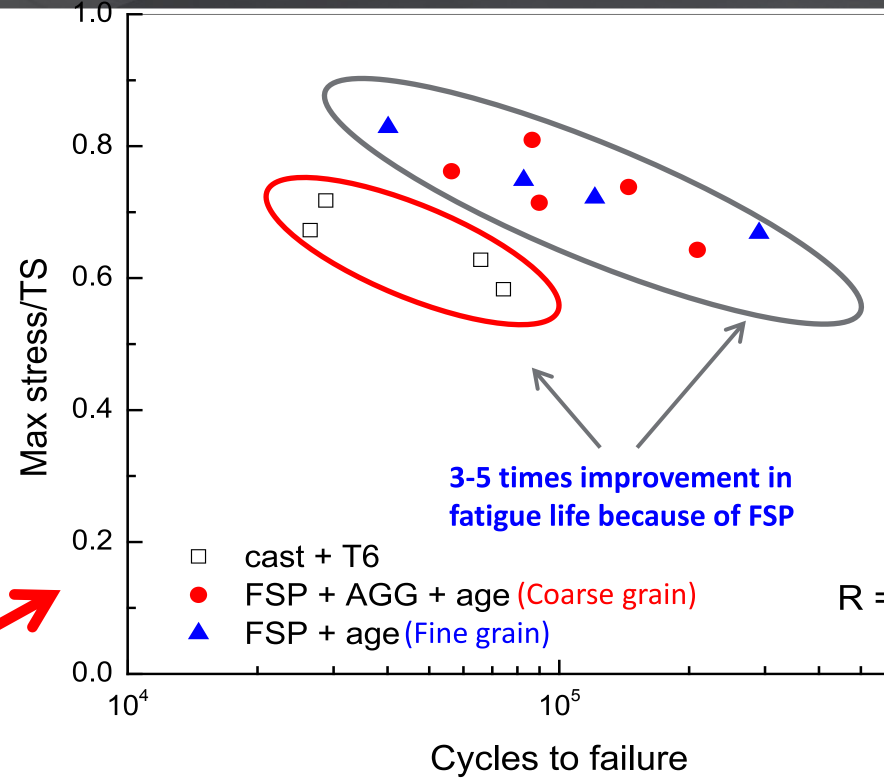
Mini-fatigue sample geometry (dimensions are in mm)

- Fatigue tests have been conducted at room temperature, and at 150ºC in an oil bath immersed test frame to determine S-N plots. Testing at 200ºC and 250ºC in progress.

Technical Accomplishments and Progress
S-N plot : Testing at 150ºC



Initial testing at elevated temperature shows better fatigue performance for FSP microstructure.



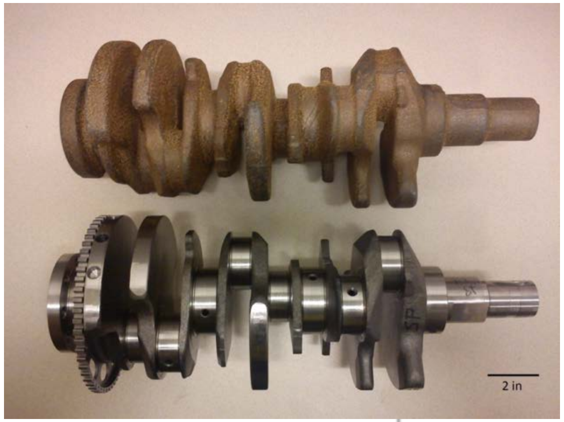
Fatigue test conducted at UNT

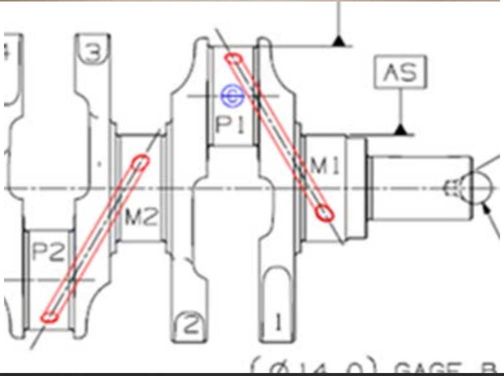
- When normalized to the respective TS of each class of microstructure, improved fatigue performance at 150ºC is clearly evident for both FSP microstructures.
- Note: these improvements are over an already good microstructure (chill cast Sr modified alloy)
- The coarse grained microstructure retains higher strength at elevated temperature with a very good fatigue performance. May be seeing effect of creep/fatigue resistance here. Tests at higher temperatures may define this better.

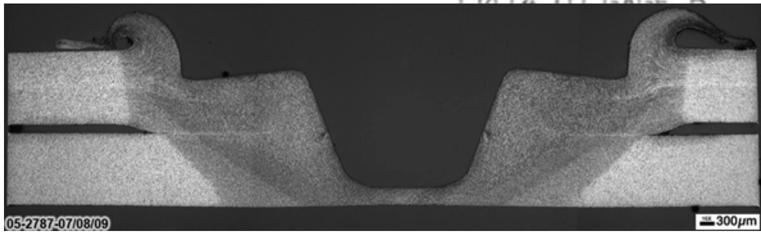
Task 2 Cast Micro-alloyed Steel

Fillet, oil hole, and flange fatigue performance improvement on rotating shafts

- Cast billets of crankshaft micro-alloyed steel have been received
- These have been section into 50 flat plates 5.5 inches diameter x 1 inch thick for linear and Spot (FSSW) processing trials
- RBF test specimens have been designed based on measured depths that will need to be processed on the unmachined crank blank in the later phases of the project
- Tool pin length and design has been completed based on the penetration depth need to produce a processed region around an oil hole
- FSP trials on the cast plates have not yet begun. (We are behind in time on this task, but not in budget allocated)







FSSW in a DP780 steel showing the processed region

Response to Previous Year Reviewers' comments

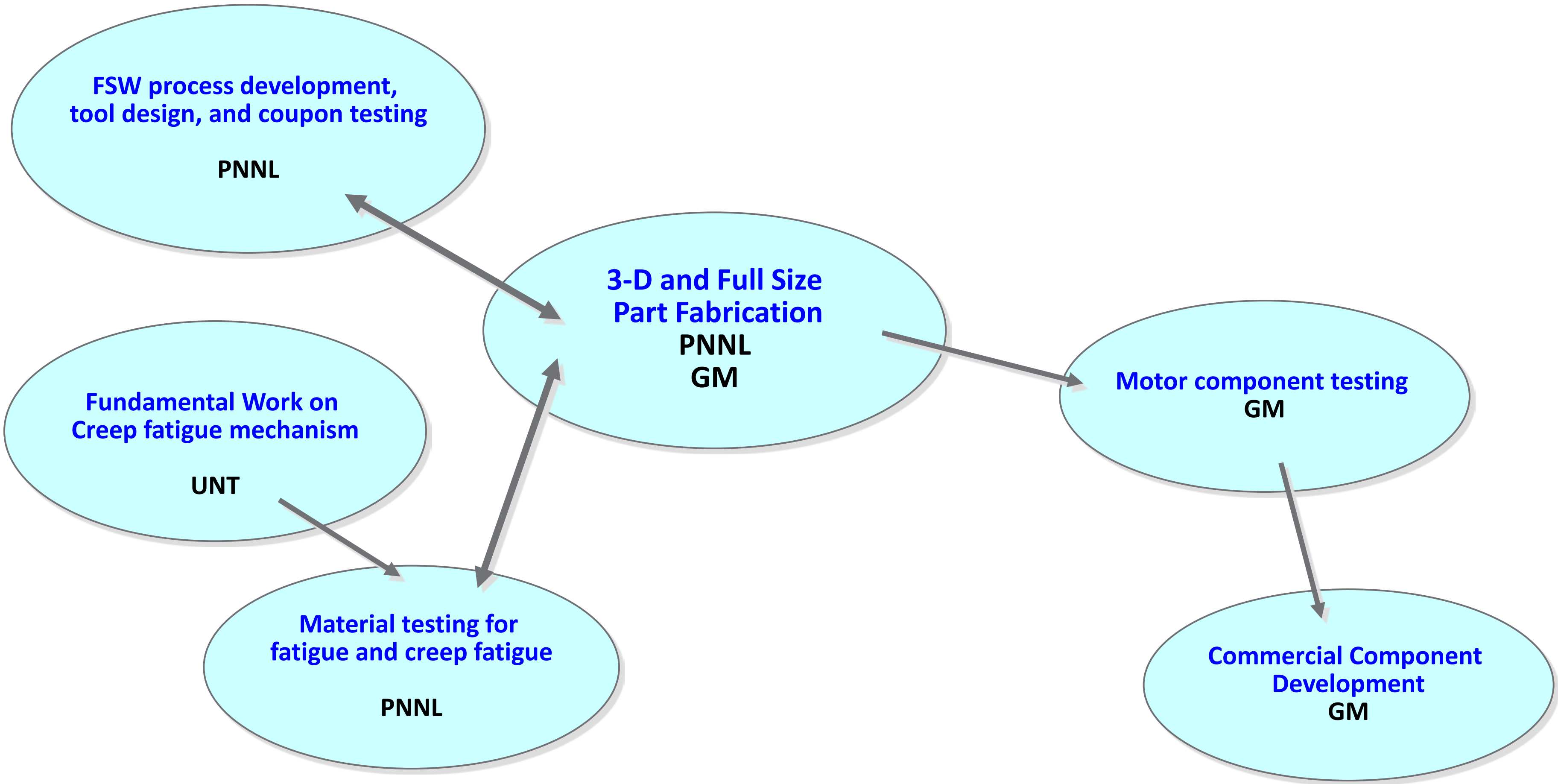
- "The reviewer thought that FSP was unlikely to provide any measurable benefit for forged crankshaft."
  - Response: We agree that FSP has the highest benefit to a cast microstructure that may have casting inhomogeneities including porosity or other metallurgical notches. The concept is to apply a secondary process to selective areas of the cast crankshaft to locally improve the properties only where they are needed. The concept includes the notion that, in general, strength requirements of an assembly are often driven by a limited number of highly loaded small areas on a complex part. Failure in these areas can drive global section thickness or strength requirements. If just those selected areas could be improved to the strength, or more importantly the fatigue and toughness requirement, then overall material or cost savings could be achieved. A cast part might be able to replace a more expensive forged part.
- Numerous reviewers commented on the issue of "how creep-fatigue will be addressed", and on the mechanism of creep as it relates to a FSP microstructure
  - Response: Results at 150C show that FSP does improve fatigue properties (both fine and coarse FSP microstructures). To address the role of microstructure and hence determine creep-fatigue mechanism, a detailed testing plan is being executed that involves extensive microscopy to characterize failure mechanism. This work will be carried out in close collaboration with UNT, Dr Rajiv Mishra who has over a decade of experience in the fundamental study of Friction Stir Processing mechanisms and microstructure property relations, including modeling the creep fatigue interaction.

Milestones

- 2013 Milestone: Demonstrate fully consolidated and microstructurally stable friction processed regions on specialized head alloy plates provided by GM. Test these processed regions at the coupon scale for microstructural stability at elevated temperature by subjecting them to heat treatment and examination for grain growth effects. (Completed)
- 2013 Milestone: Demonstrate that room temperature fatigue performance in the FSP processed coupons can achieve a minimum 10% improvement over baseline alloys (Completed)
- 2013 Milestone: Investigate fundamental aspects of elevated temperature creep-fatigue mechanisms as they apply to friction processing and describe through reporting the correlation between FSP process parameters and creep fatigue performance. (Completed for fine and coarse grained FSP microstructures tested at 150C. More testing at higher temperature to better define the creep contribution is in progress)
- 2014 Milestone (March): Develop the process, tools, and techniques to create a FSP processed region on a rotating shaft such that the region will be in a fillet configuration after machining. Produce a demonstration article in aluminum that demonstrates the concept. (Milestone postponed so that Oil hole fatigue improvement tests could be accomplished first)
- 2014 Milestone (June). Develop the FSP process, tools and control necessary to produce defect free FSP regions in a cast steel typically used in crankshaft applications and characterize microstructure. (on track)

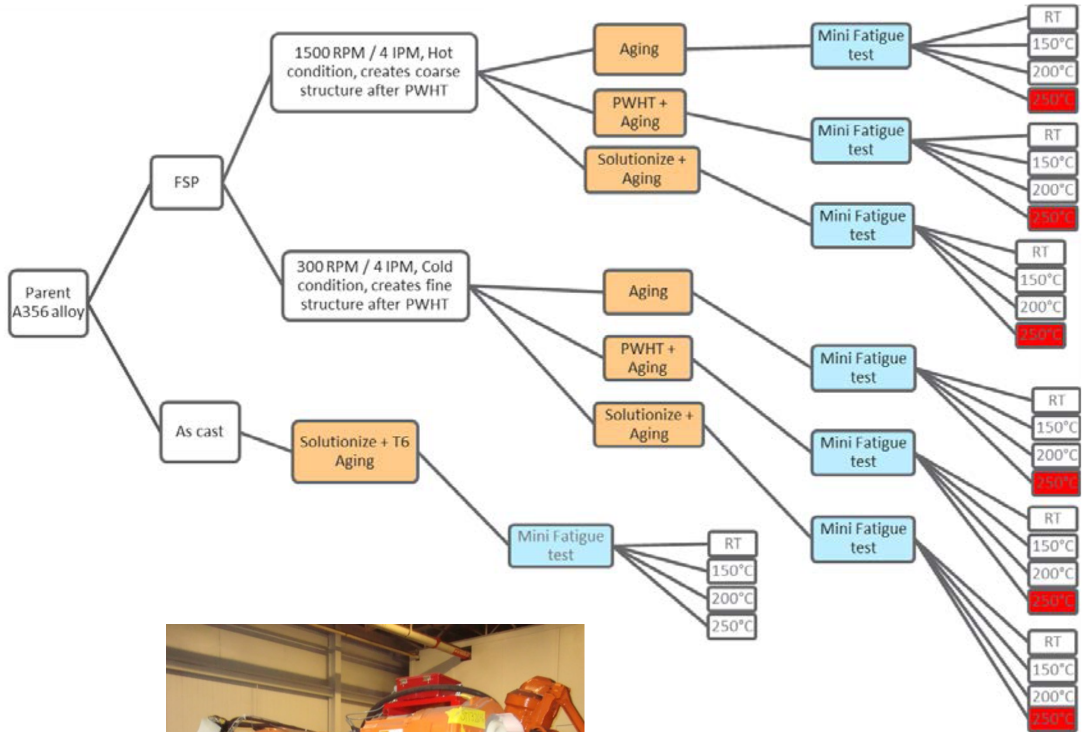
Collaboration and Coordination with Other Institutions

Technology Transfer / Collaborations



Future Work
Task 1 Aluminum

- Continuation of elevated temperature fatigue testing. Testing details shown on slide 14. We are about 50% through this testing matrix.
- Details of a specific 250 C Creep/ Fatigue Test need to be worked out (cyclic – hold test)
- More testing should reveal the role of microstructure. Post-mortem analysis of failed samples will bring out the dominant failure mechanism at elevated temperature.
- FSP processed regions on the prototype cylinder head will need to be done in a 3-d configuration, so late FY14 we will begin programing our ABB IRB 7600 robot that has a FSW head as an end effector.



Future Work
Task 2 Steel

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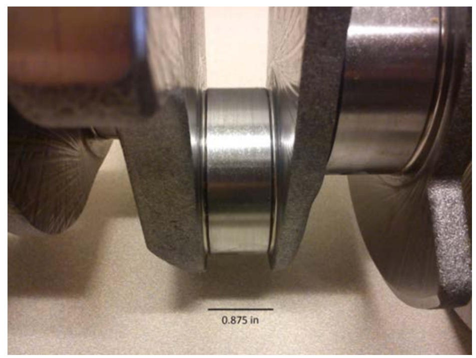
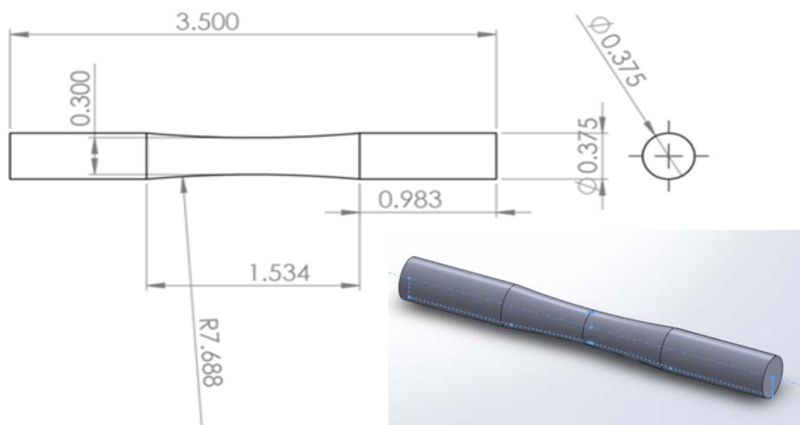
Targeted Concepts

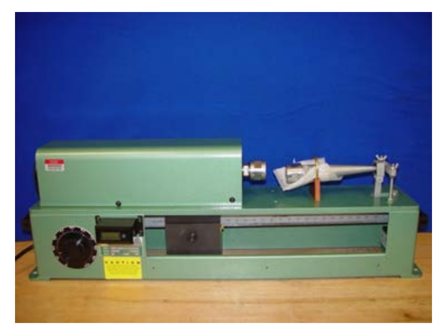
- Oil hole fatigue failure in chamfer
  - FSSW, or sweeping spot weld
- Fillet fatigue
  - Might only be able to reach fillets on mains





Test plan:

- Make linear welds and swept spots in provided flat plates
- Cut out round bar specimens for RBF testing
- Specimen types
  - RBF specimen of baseline material
  - RBF specimen with hole drilled to ½ of the specimen diameter, hole chamfered, then induction hardened to spec.
  - RBF specimen FSP processed with hole drilled in processed zone then induction hardened to spec (not chamfered to test if chamfering can be avoided)



Summary

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Increasing the durability of engine components can increase the operational envelopes of the engine, allowing designers of the combustion process to access areas of engine control where increased specific power and low emission levels are found, but where high PCPs can create reliability problems.

- FSP has been demonstrated to produce significant improvement in room temperature fatigue and durability in even high quality castings (small SDAS, small eutectic particle size) . Selective applications in block, or in cooler locations on the head, and certainly all steel applications are expected to benefit from FSP under normal fatigue failure mechanisms.

- Friction stir processed material, especially if processed to produce an AGG microstructure, has shown an order-of-magnitude improvement in RT fatigue life, and a 3-5 times improvement at 150 C, far exceeding the project milestones.

- Some areas of the cylinder head (e.g., the valve bridge area or near the combustion chamber) are at a significantly high temperature. At high temperature the failure mechanisms are a mix of classical fatigue and creep. FY 2014 work will focus on elevated temperature creep and fatigue testing to see how FSP microstructures will affect elevated temperature performance.

- The steel FSP work also focuses on cast materials, and will address the application of FSP to mitigate fatigue failure at the oil hole chamfer region, and on fillets on rotating shafts. This work is aimed at enabling lower cost materials while still achieving the performance required by more energy efficient combustion strategies.